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Hygrothermal Study of a House Made of Local Biosourced Materials Based on Clay: Experimental Study

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Abstract

The purpose of this study is to experimentally analyze the thermal behavior of the walls of a prototype experimental house. A Datalogger and thermocouples were used on the experimental house to determine the temperatures of the exterior and interior walls. Also, "MSR" type HygroPuce was used to determine the exterior and interior temperatures and relative humidity of the habitat. The results show that a wall made of bio-based materials with a mixture of "earth + *Hibiscus cannabinus L.* fibers" allows reducing the fluctuations of the interior temperatures. We observe the peaks of temperatures on the external walls at 11:00 am and for the interior walls, the peaks are observed at 5:00 pm. The maximum thermal phase shift between the peaks of the external and internal temperatures is about 7.5 hours, and the maximum damping factor is 0.9. Also, we note that the thermal performance of the material used in the design of the envelope of the house is determined by the improvement of the response of the envelope in front of the external thermal solicitations.

Keywords

Thermal Dephasing, Damping Factor, Thermal Comfort, Bioclimatic House

1. Introduction

The need for thermal comfort in buildings, whether for residential or office use, is one of the most important requirements that leads designers to consider design techniques in general and the nature of building materials in particular. Nowadays, the real challenge in construction is to ensure the indoor air quality of the dwellings to the occupants. Latha *et al.* [1] have shown that thermal comfort has an impact on the productivity and health of occupants. However, ensuring thermal comfort in buildings in sub-Saharan areas and in countries where energy is a scarce commodity can be difficult due to the very limited financial capacities of the populations. The "UN-HABITAT" focal point in Senegal indicated that buildings consume nearly 50% of final energy in Africa [2]. In Burkina Faso, 60% of the energy consumed in the building sector is devoted to air conditioning while the country has a low electrification rate (about 22.57% in 2019) [3]. This high energy demand in the building sector is undoubtedly linked to the transposition of Western construction techniques that are not adapted to the African context and are energy intensive [4].

In sub-Saharan Africa, where the climate is hot and dry, solutions to mitigate the heat flow related to outdoor stresses rely on architectural design and the selection of appropriate building materials. An architectural design oriented towards the development of technologies adapted to the climatic, social and cultural contexts recommends the use of local building materials such as biosourced earth-based materials. Earth, used for thousands of years in construction, is a material with high thermal inertia and very high thermal performance [5]. It is one of the oldest building materials of humanity and according to UNESCO 20% of the sites registered as world heritage are entirely or partially built on earth, which reflects the rich architectural heritage of the earth material. [6].

Indeed, ancient architecture uses heavy earthen materials in the design of exterior walls to buffer uncontrolled increases in outdoor temperatures. This design provides a very important thermal mass to the exterior walls and makes them very efficient against overheating by increasing their capacity to store heat [7]. For centuries, the various forms and techniques of earthen construction have made it possible to erect sustainable buildings thermally adapted to the climate of all inhabited continents. These technologies have evolved over time according to the need for scientific recognition and thermal comfort, and today we speak of "bioclimatic" architectural. It is a design that uses available local resources and reduces the heat exchange between the outside atmosphere and the air of the interior environment [8]. Indeed, this architectural called "ecological" is the regard of all the processes respectful of the environment and house, in the sense that it can reduce energy demand and emissions of greenhouse gases [9] [10]. The use of local biosourced materials based on earth proves to be a wise choice because they are materials that offer very good thermal inertia to the envelopes of houses. From there, we ask ourselves the following question: "how to optimize the thermal comfort of the houses with the available local and natural resources?" It is in this perspective that we propose to carry out an experimental study of a prototype of experimental house.

2. Methodology

2.1. Description of the Experimental House

According to Decree N°2009-219/PRES/PM/MHU of 20 April 2009, determining the characteristics of decent houses in Burkina Faso, the basic unit recommended by this decree is a F3 dwelling (two bedrooms + one living room + one shower) [11]. The dimensions to be respected are: 9 m^2 for the bedrooms, 16 m^2 for the living room, 7 m^2 for the kitchen and 1.8 m^2 for the shower. In the hypothesis that even with a house of type F3, the measurements will be made only on a thermal zone (example of the room of 9 m^2), we realized a prototype of house of an area of approximately 9 m^2 for this experimental study. **Figure 1** illustrates the layout plan the experimental house.

The walls of this test house are made of biosourced earth bricks (mixture of earth + *Hibiscus cannabinus L.* fibers) of dimensions L * l * E = 30 * 14 * 10 cm and joined with mortar of the same mixture; the roof has a cover of aluminum-zinc sheet metal; the attic is naturally ventilated thanks to circular holes; the ceiling is made of plywood of 5 mm thickness The door and the window are in single glazing of 5 mm thickness with iron frames. **Table 1** summarizes the thermophysical properties of the materials used in the construction of this experimental house.

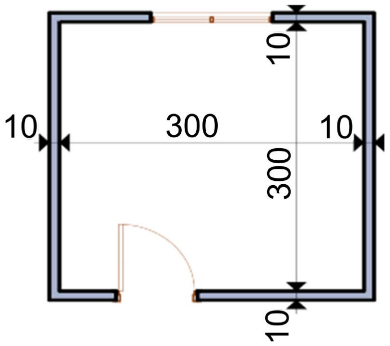

Figure 1. Implantation plan.

Table 1. Thermal properties of materials used in the construction of the house.

Materials	thermal conductivity (W/m·K)	Thermal capacity (J/kg·K)	Density (kg/m^3)
Sheet metal (aluminum)	230	897	2700
Biosourced earth bricks	0.80	2062.81	1669.73
Mortar (clay + hibiscus cannabinus L. fibres)	0.80	2062.81	1669.73
Coating (sand + cement)	0.87	105	2200
wood glazing	1.15	1000	840

2.2. Wall Configuration

The house is built under real conditions taking into account climatic hazards (rain, wind, sunshine, etc.). Therefore, the walls made of biosourced earth bricks are covered with cement coatings (interior and exterior) of 7 cm thickness. This gives us a configuration in which the thermal mass, *i.e.*, the envelope in biobased earth bricks, is "sandwiched" by the plaster. The main facade of the house is oriented North-South.

2.3. Occupancy Scenario

The experimental study of the house consisted in measuring the temperatures on its walls (interior and exterior), the temperature and the relative humidity of the interior and exterior air. In order to take into account, the real climatic conditions during the measurements, a bibliographical study of the outside atmosphere (temperature and outside radiation) according to the periods and the hours was carried out on the site where the house is implanted. Thus, the measurements are carried out under conditions such as the door remained closed and the window remained open continuously; there is an exchange of air by natural ventilation between the indoor and outdoor environment through the window.

2.4. Data Acquisition Protocol

A Midi-Logger GL840 datalogger with 20 channels is used to record temperatures using type "K" and "J" thermocouples with uncertainties of about 1.6˚C and 1.7˚C respectively. As for the relative humidity of the indoor air and the outdoor environment, it was measured with autonomous and programmable humidity recorders of the "MSR" type.

The instrumentation of the different walls of the house was carried out simultaneously to ensure the uniformity of the climatic parameters (outdoor temperature and global sunshine) that we measured during the period of data taking at the house. Thus, this instrumentation is made so as to:

- Place a thermocouple (1.5 m from the ground) on each of the four (04) exterior and the four (04) interior faces of the house to measure the outside temperatures on the walls;
- Install a thermocouple on the outside surface of the roof to measure the outside temperature;
- Place a thermocouple on the interior surface of the false ceiling to measure its temperature;
- Place a thermocouple on the floor to measure its temperature;
- Hang a HygroPuce inside the house to measure the temperature and humidity of the indoor air;
- Introduce a HygroPuce in the attic of the false ceiling to measure the temperature and relative humidity of the air circulating there.

The installation of the thermocouples on the surfaces is done with an adhesive element (adhesive tape) and protected with glass wool.

The acquisition and recording of the measurements are carried out every five (05) minutes. At the end of the measurement period, the data stored in the memory of the Datalogger and the HygroPuce are transferred to a suitable medium and processed on a computer using a well-adapted software. Figure 2 below is a schematic of the principle used for the instrumentation, acquisition and processing of the tracked data in this study.

2.5. Method of Evaluating the Thermal Dephasing and Damping Factor

The thermal dephasing or time lag is the time difference that exists between the maxima of the exterior and interior temperatures. It is a parameter that informs us of the capacity of the envelope of the house to oppose the effects of the thermal solicitations imposed by the external environment to the interior air. This parameter allows translating the capacity of the wall to accumulate heat; that is to say to lengthen the time taken by the heat to cross the wall. The greater the thermal dephasing, the longer it will take for the external stresses to influence

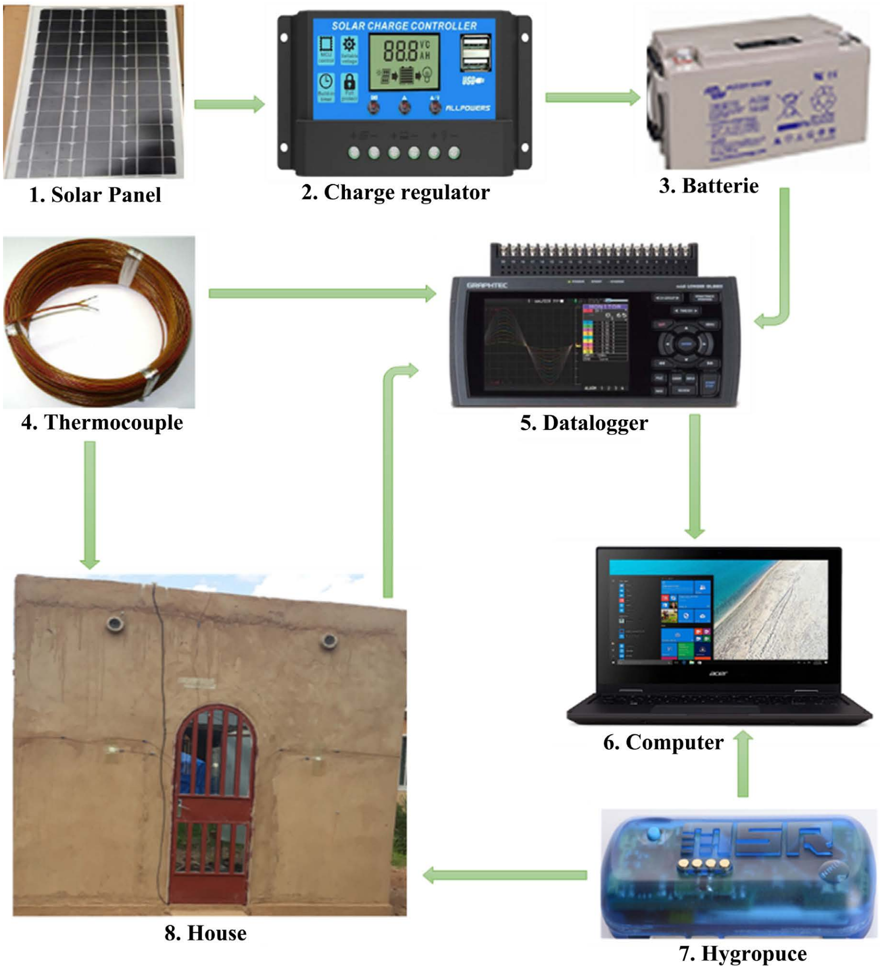

Figure 2. Instrumentation, data acquisition and processing.

the indoor environment. From our results, we notice that the outside air temperatures reach their peaks between 12:00am and 2:00pm. Therefore, a long phase shift will allow attenuating the amplitude of the indoor temperature because at the moment when the outdoor heat will reach the indoor, the outdoor temperature will be decreasing. Several methods exist in the literature for the evaluation of this parameter among which the relation of Layal CHAHWANE whose expression is the following [12]:

$$\phi = t_{T_{\text{in,max}}} - t_{T_{\text{out,max}}} \tag{1}$$

ϕ: thermal dephasing in hours (h);

$t_{T_{\text{in,max}}}$: the date on which the inner amplitude is reached (h);

$t_{T_{\text{out,max}}}$: the date when the external amplitude is reached (h).

The damping factor is the ratio of the maximum values of the outdoor and indoor temperatures and represents the ability of the house envelope to dampen indoor temperature fluctuations. The lower the damping factor, the more interior temperatures are damped. It is determined from the relation:

$$f = \Delta T_{\text{in}} / \Delta T_{\text{out}} \tag{2}$$

3. Results and Discussions

3.1. Meteorological Parameters

3.1.1. Overall Sunshine

In **Figure 3** we have represented all the sunshine data collected over a period of ten (10) days. From this figure, we note that the maximum values of sunshine are above 800 W/m². Referring to the meteorological data of the city of Ouagadougou found in the literature, we can affirm that the solarimeter gave the real climatic parameters of our study site.

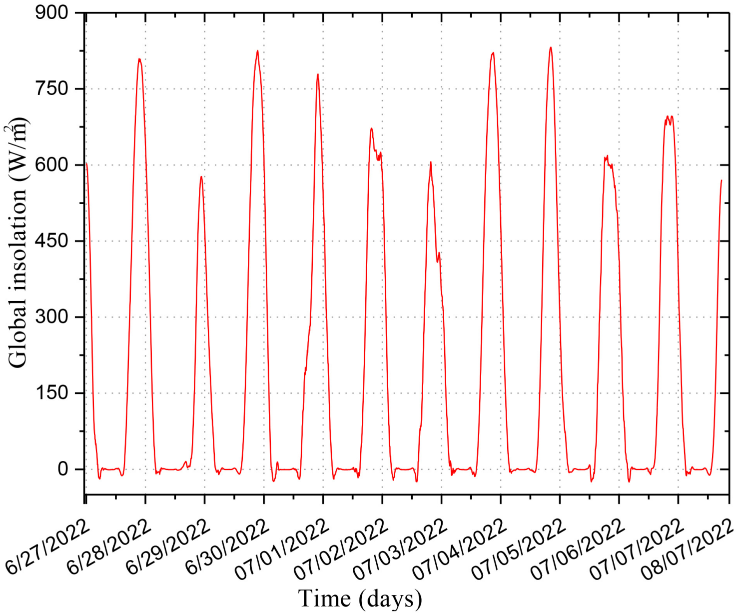

Figure 3. Overall sunshine on the site.

3.1.2. Temperature of the Outside Environment

The outdoor air temperatures recorded vary between 24.5˚C and 37˚C and respect the variation of the meteorological data of this period of the year (beginning of the rainy season). The maximum values are recorded between 11:00 am and 2:00 pm as shown in **Figure 4** and correspond to the hours when the solar flux is also important. However, the minimum temperatures are observed at times when solar radiation is non-existent, between 7:00 pm in the evening and 5:00 am in the morning.

3.1.3. Relative Humidity of the Outside Air

Figure 5 illustrates the evolution of the relative humidity of the outdoor environment. They vary from 44% to 87%. We note that the periods of high relative humidity correspond to periods of low temperatures of the outdoor environment. Indeed, the values of relative humidity measured are relatively higher because of the period concerned for these measurements; it is the beginning of the winter season in Burkina Faso.

3.2. Evolution of Temperatures on the Walls of House

3.2.1. Outside and Inside Temperature of the East Wall

Figure 6 below shows the variations of the experimentally measured temperatures on the outer and inner walls of the East wall (*TPE_out* et *TPE_in*) of the cell. The outside temperatures vary from 25˚C to 45˚C; while inside they vary from 26˚C to 38˚C. The difference between the two maximum values is important; this can be justified by the fact that this surface is well sunny according to the orientation of the house. We notice that during the whole period of the measurements, the indoor temperatures remain low compared to the outdoor temperatures. This difference in the level of heating of the two surfaces could

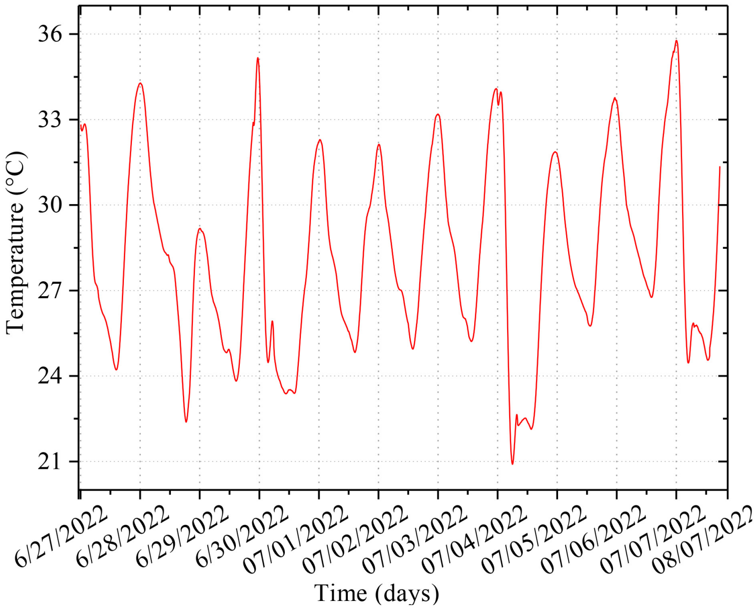

Figure 4. Evolution of outdoor air temperatures.

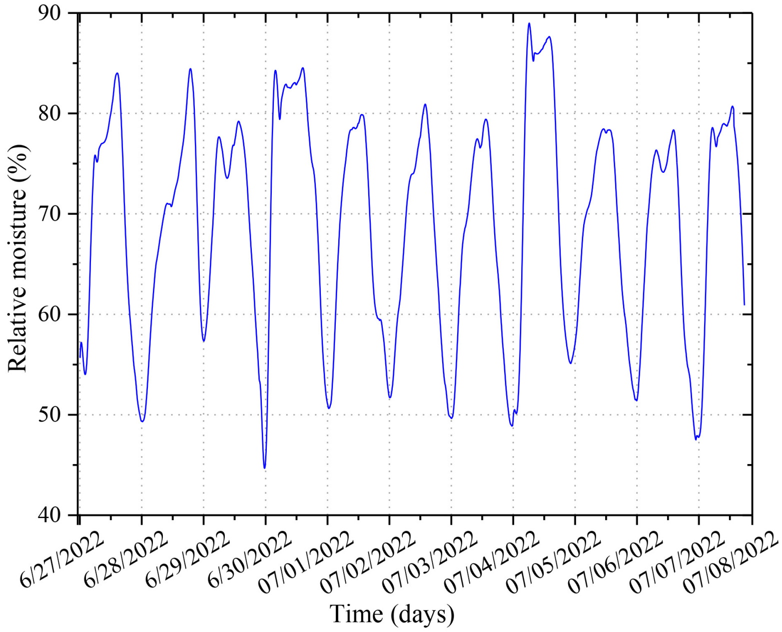

Figure 5. Evolution of the relative humidity of the outdoor environment.

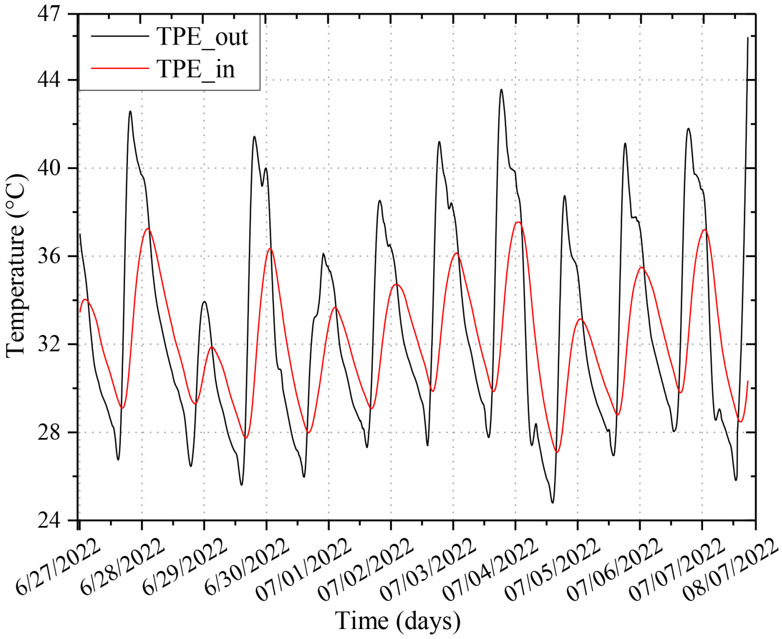

Figure 6. Exterior and interior temperature variations of the East wall.

be related to the nature of the wall which would delay the transmission of heat from the outside to the inside.

3.2.2. Exterior and Interior Temperatures of the West Wall

In **Figure 7** we have represented the variation of the temperature of the exterior and interior sides of the West wall (*TPO_out* et *TPO_in*). The maximum and minimum temperatures on the outer wall are respectively about 43˚C and 26˚C; while on the inner wall they are about 39˚C and 32˚C. On this wall, we note

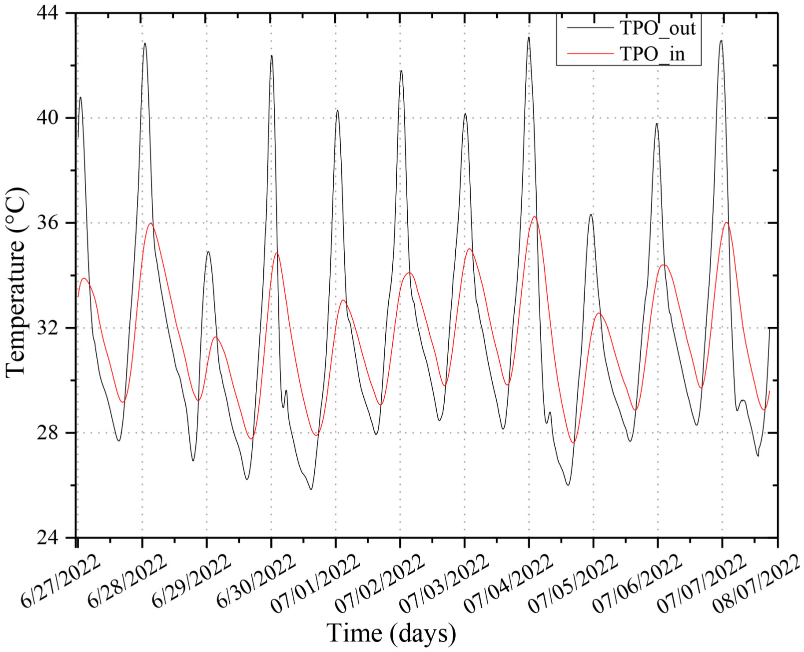

Figure 7. Exterior and interior temperature variations of the West wall.

that the hypothesis that the nature of the wall would delay the diffusion of heat is confirmed. The minimum outside temperature is much lower than the minimum inside temperature. Since this wall will be well exposed to the sun at times when the temperature of the outside environment starts to drop, its inside face will receive only a small part of the heat it receives.

3.2.3. Outside and Inside Temperature of the North Wall

Figure 8 represents the evolution of the outside and inside temperatures on the north wall of the cell (*TPN_out* et *TPN_in*). In a similar way as in the previous cases, we notice that the temperatures are very damped from the outside to the inside. The minimum and maximum temperatures reached on the external wall are respectively 25˚C and 41˚C approximately; whereas on the internal wall, they are respectively 27˚C and 37˚C approximately. Here, the orientation of the wall could influence the evolution of the temperatures taking into account that it does not receive directly the solar flux. It is the mode of heat transfer by convection that is most important on this wall.

3.2.4. Outside and Inside Temperature of the South Wall

The temperatures of the exterior and interior sides (*TPS_out* et *TPS_in*) of the south wall are shown in **Figure 9**. They have the same profiles as the temperatures on the other walls. On this wall, the maximum and minimum temperatures are respectively 38˚C and 25˚C on the external surface; while on the internal surface they are respectively 36˚C and 27˚C. The variation between the exterior and interior is not remarkable enough; this could be justified by the fact that the house is oriented North-South and at this time of the year the south wall does not receive enough sunlight.

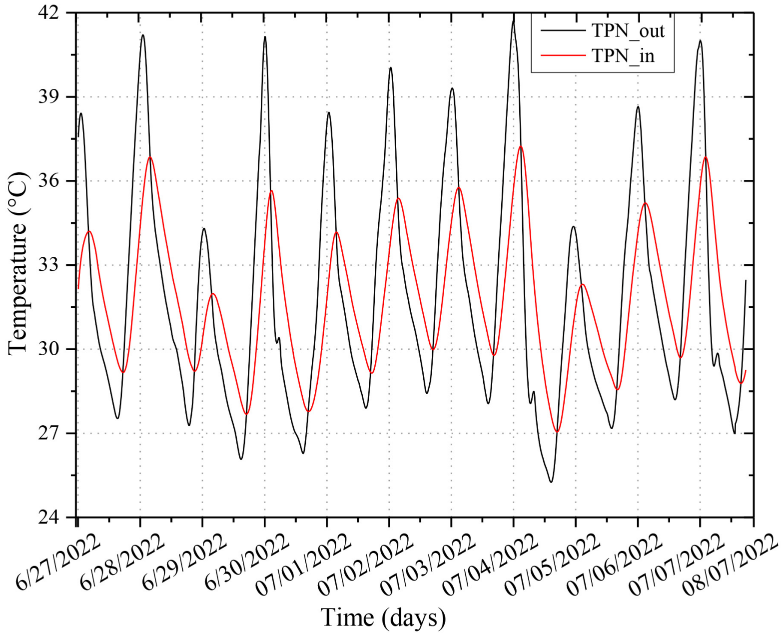

Figure 8. Variations of the external and internal temperatures of the north wall.

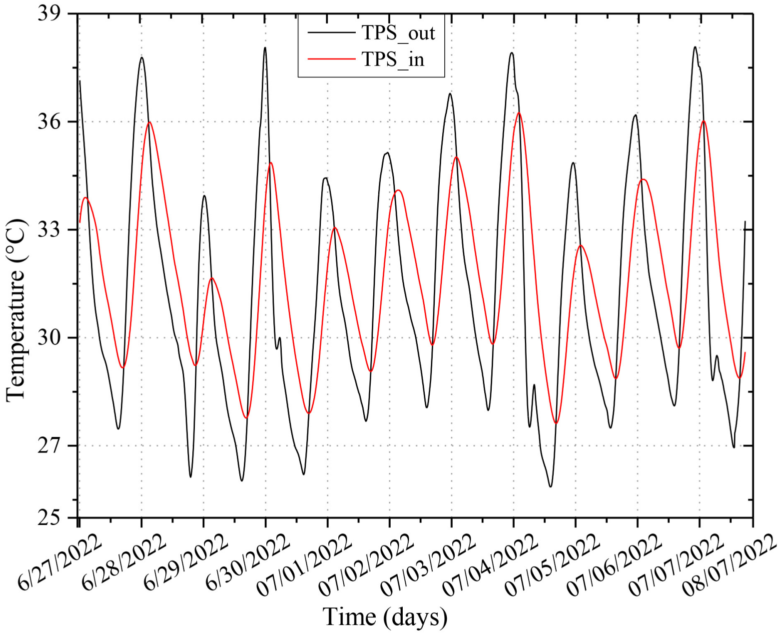

Figure 9. Variations of the exterior and interior temperatures of the south wall.

3.2.5. Evolution of Roof, False Ceiling and Indoor Air Temperatures

We have represented in Figure 10 the temperature variations on the roof (***Troof***), the interior face of the false ceiling (***Tfp_in***) and the interior air temperature (***Tair_in***) of the cell during the period from 27/06/2022 to 08/07/2022. The analysis of these results allows us to say that the roof is the part of the house where the temperature variations are the most important. On the roof, the temperatures increase considerably until reaching a maximum of 58˚C during the day and during the night the temperatures drop significantly to reach minimums

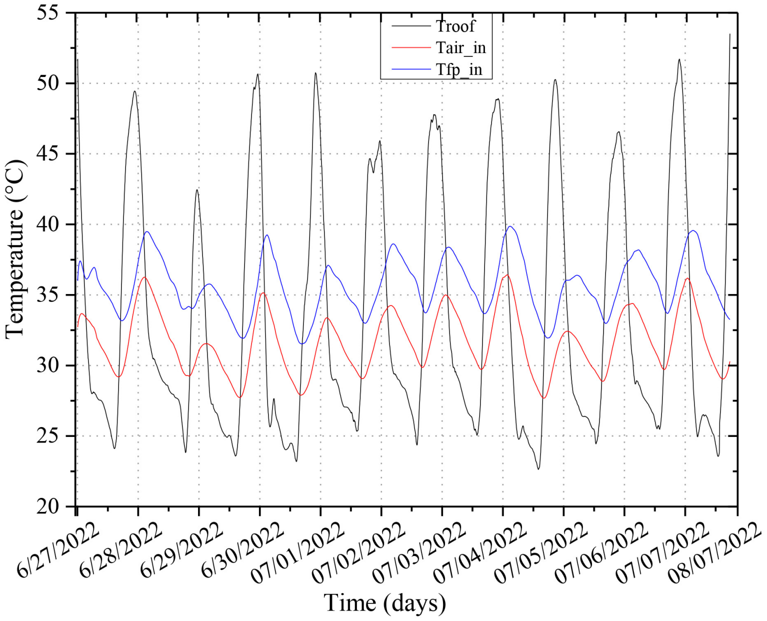

Figure 10. Temperature variation on the roof, the false ceiling and the indoor air.

of about 23˚C. This variation would be due to the nature of the material (aluminum) which is a good conductor of heat. We note that the variation of temperatures on the false ceiling is proportional to the variation of temperatures on the roof. However, they are damped by the air confined between the false ceiling and the sheet metal. The thermal exchanges between the interior air and the various interior facades of the house are done by thermal convection, the evolution of the temperature of the interior environment is thus the contribution of these surfaces.

3.2.6. Evolution of Roof, Floor and False Ceiling Temperatures

We have represented in Figure 11 the temperature variations on the sheet metal (***Troof***), the interior face of the false ceiling (***Tfp_in***) and the temperature on the floor surface (***Tpl***) of the cell during the period from 06/27/2022 to 07/08/2022. We find that the temperature variation on the floor has the same pattern as that on the plywood. However, the temperature variation on the floor is very damped compared to that on the plywood. This is due to the fact that the ground on which the floor rests is a material of greater thermal inertia that tends to maintain its temperature constant. It can therefore be said that the heat exchange on the floor is strongly influenced by thermal convection.

3.2.7. Evolution of the Temperatures of the Outdoor and Indoor Environments

The temperature variations of the air inside and outside the cell (Figure 12) show that they are very damped from the outside to the inside. Outside, the maximum temperature value is about 46˚C; while inside it is about 37˚C. We also notice that the minimum temperatures outside and inside are respectively 25˚C and 27˚C. Moreover, these maxima and minima are not reached at the same time;

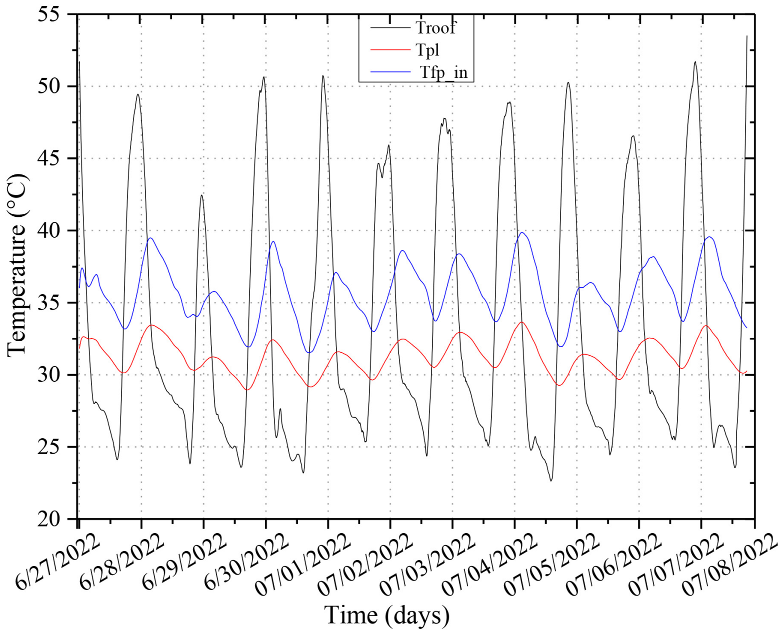

Figure 11. Variation of temperatures on the roof, false ceiling and floor.

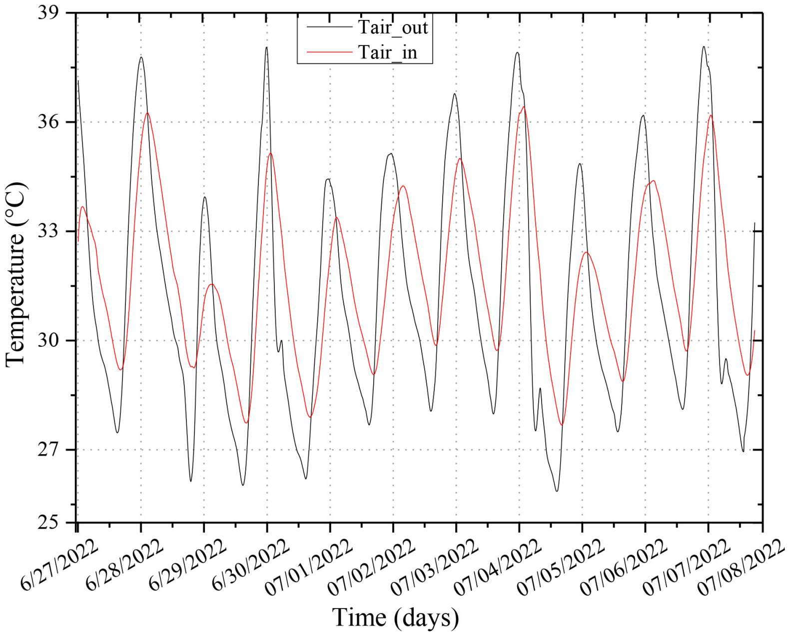

Figure 12. Variation in temperature between the outdoor and indoor environments.

there is a significant phase shift between the two temperature peaks. We observe the same phenomenon on the temperatures of the exterior and interior walls; this could be justified by the fact that the envelope of the house would delay the transfer of heat from the exterior to the interior.

3.2.8. Evolution of Indoor and Outdoor Relative Humidity

The analysis of the variation of the relative humidity of the air outside and inside the cell shows that they are damped by the envelope of the house (**Figure 13**).

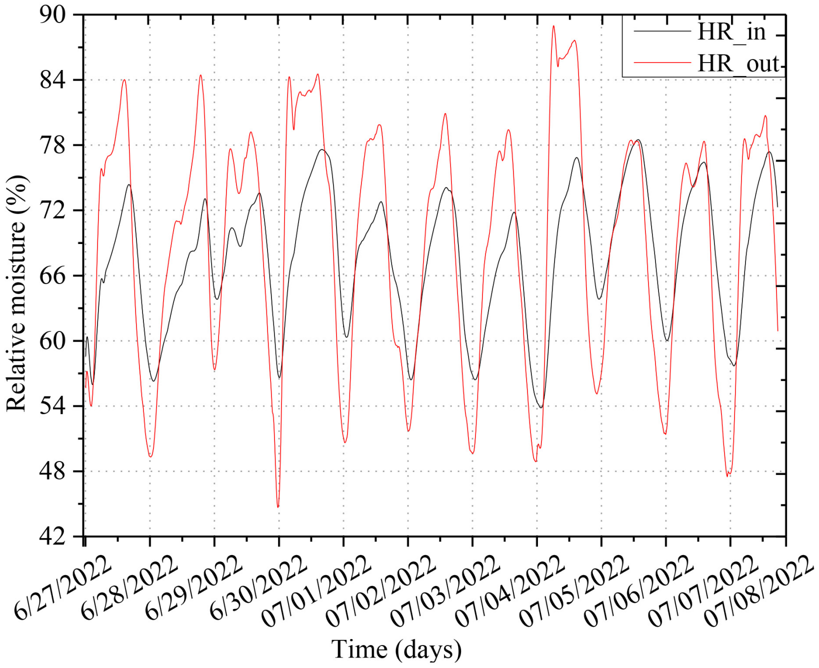

Figure 13. Variation in outdoor and indoor relative humidity.

The maximum values are about 87% and 80% outside and inside respectively. This difference could be explained by the fact that the air exchange rates between the interior and exterior are important. We note that on all ten (10) days of measurement, the relative humidity of the air inside the house are below those of the air of the outdoor environment. Also, given that during this period it rains, we noticed that the values are very high on days when there are storms. According to the nature of the building material, raw earth bricks, the envelope is quickly impacted by the hygrometry of the outside environment. From the analysis of these results, we can see that the infiltrations and the nature of the material influence the evolution of the relative humidity of the exterior and interior environment.

3.3. Thermal Dephasing and Damping Factor

3.3.1. Thermal Dephasing

By applying the equation [1] to the temperatures taken on the four (04) facades of our experimental housing prototype, we obtained the thermal dephasing between the peak outdoor and indoor temperatures, over ten (10) days, represented in **Figure 14**. These results show that the responses of the East wall show more similarities during the whole measurement time, where the average difference between indoor and outdoor temperatures varies between 1˚C and 3˚C. The average thermal dephasing observed on this wall is 6 h although the temperature peaks are reached very quickly (around 10 hours) outside. This observation is justified by the fact that this wall is heated by the solar rays very early in the morning depending on its orientation. On the other walls of the house, the temperature peaks are reached with a slight delay compared to those of the east wall

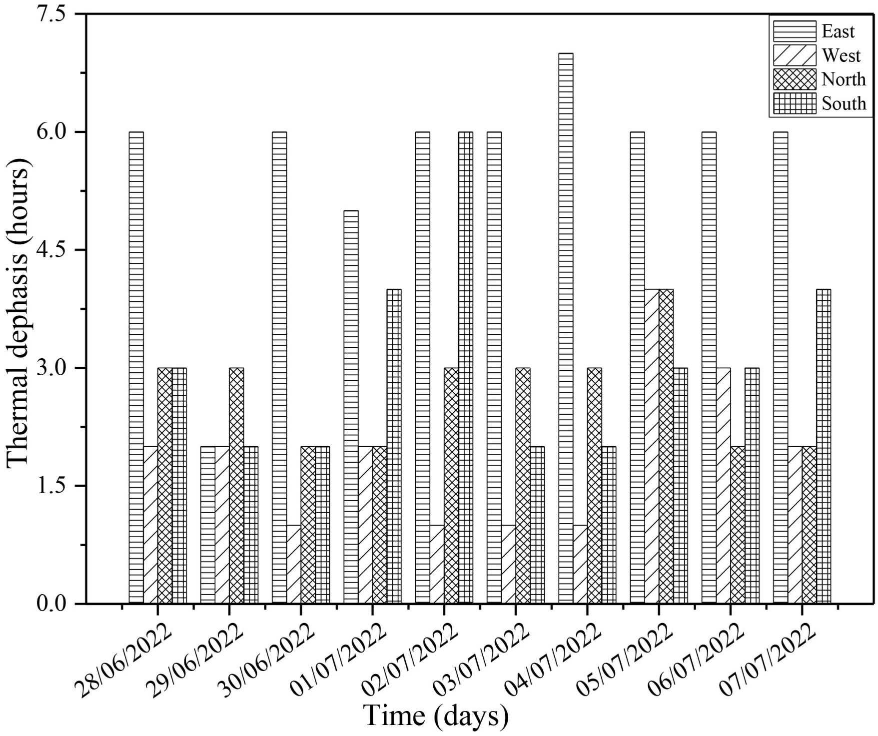

Figure 14. Thermal dephasing of the four (04) facades of the house.

because these walls do not receive direct solar radiation; they are heated by convection phenomena with the ambient air. However, the peaks of the interior temperatures are reached almost at the same time. Considering the path of the sun and the period at which the interior temperatures reach their peaks, it is the east wall that informs us of the behavior of the envelope of the house in front of the external stresses. By comparing our results with the results of the work of ZOMA Fati on the simulation of the thermal response of a wall built in cement block [13] we can affirm that the response of the envelope of our house is interesting for the interior comfort.

3.3.2. Damping Factor

Indeed, the application of this relation [2] to the evolution of temperatures on the different walls of our experimental house built with biosourced materials based on earth, allows us to obtain the damping factors represented in **Figure 15**. These results show that over the ten (10) days of measurement, the West wall has the best damping factor with the most interesting value found on July 02, 2022. In addition, we observed that the East wall in addition to having the best thermal phase shift has a relatively interesting damping factor with an average difference of 0.15 compared to the West wall. The North and South walls have very close damping factors and are the highest. Therefore, the temperatures are less damped on these walls. In general, we can say that the envelope of the house has a good thermal inertia because the damping factors are interesting on all its walls except on the South wall.

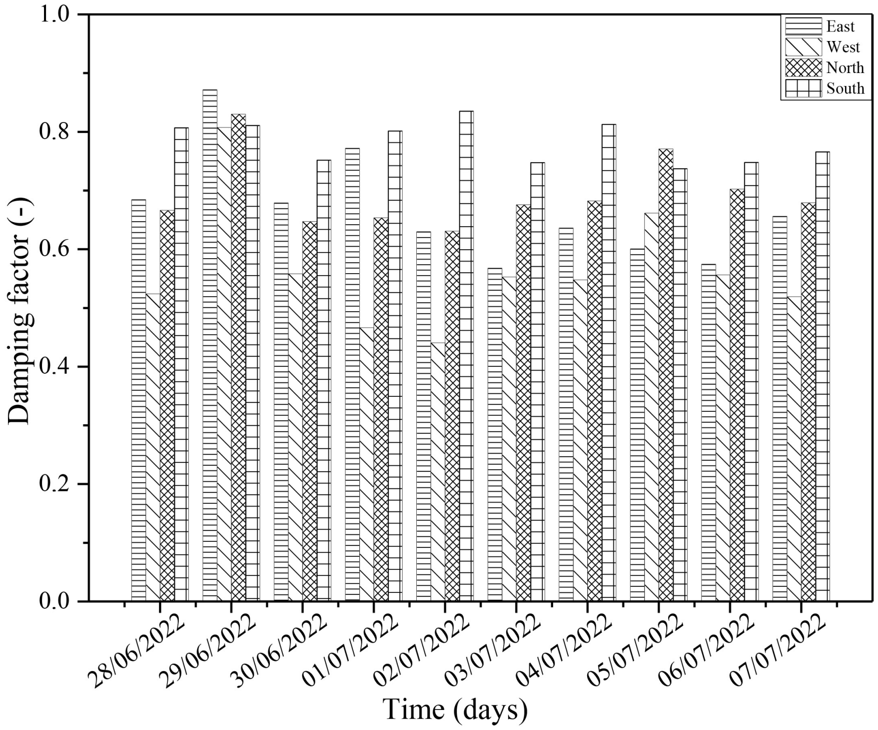

Figure 15. Damping factors of the four (04) walls over ten days.

4. Conclusions

This study was devoted to the experimental study of a prototype of a typical house built with earth-based biosourced composite materials. This approach aims to contribute to the improvement of the thermal comfort in sub-Saharan zone by the use of the local resources (the ground, the vegetable fibers) available. Indeed, we have, with the help of appropriate equipment, measuring the temperatures of all the components of the house, the relative humidity inside and outside, and the amount of solar flux received by the exterior envelope.

At the end of this study, we can say that the choice of materials constituting the walls of the house and the referral of the facades of the house have a significant impact on the response of the envelope of the house to the external solicitations. Based on the thermal dephasing on the east wall, we can affirm that the envelope considerably reduces the external thermal amplitude. In general, temperatures are strongly damped from the outside to the inside. However, the roof appears to be the component on which the thermal losses are important with temperatures reaching 60˚C.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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